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Specification and Drawings, as originally filed, with Application for Patent Serial No: **2,437,323,** on August 14, 2003, by **CLAUDE ALLAIRE and ALAIN CARBONNEAU,** for "Apparatus for the Elastic Properties Measurement of Materials and Method Therefor".

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ABSTRACT OF THE DISCLOSURE

Knowledge of the elastic properties of materials is of prime importance. These properties do not only reflect the extent of bonding in the material, but also permit characterization of its behaviour under stress. For heterogeneous materials such as refractories and carbon electrodes, the measurement of such properties is difficult to achieve with high level of repeatability. The present invention is directed to a novel method and apparatus allowing the measurement of the Elastic and Shear Modulus, as well as the Poisson's ratio of heterogeneous materials, at room and high temperature, according to a non destructive acoustic technique.

TITLE OF THE INVENTION

APPARATUS FOR THE ELASTIC PROPERTIES MEASUREMENT OF MATERIALS AND METHOD THEREFOR

FIELD OF THE INVENTION

The present invention relates to properties measurement of materials.

More specifically, the present invention is concerned an apparatus for the elastic properties measurement of materials and with a method therefor.

BACKGROUND OF THE INVENTION

Sonic testing is based on time-varying deformations or vibrations in materials, which are generally referred to as acoustic. All materials are comprised of atoms, which may be forced into vibrational motion from their equilibrium positions. Many different patterns of vibrational motion exist at the atomic level. However, most are irrelevant to acoustic testing. Such testing is focused on particles that contain many atoms that move in unison to produce a mechanical wave. Provided a material is not stressed in tension or compression beyond its elastic limit, its individual particles exhibit elastic oscillations.

In solids, sound waves can propagate under different modes

that are based on the way the particles oscillate. Sound can propagate as longitudinal waves, shear waves, surface waves, and in thin materials as plate waves. Longitudinal and shear waves are the two modes of propagation most widely used in sonic testing.

When an elastic material is impacted, it resonates at a given natural frequency, which is a function of its elastic properties, i.e., E (Elastic or Young's modulus), G (Shearing or Coulomb's modulus) and (Poisson's ratio). The relationship between these properties is given by the following equation:

$$G = \frac{E}{2(1+\nu)} \qquad (1)$$

The natural resonance frequency, f, is reached when a stationary acoustic wave, of wavelength $\lambda/2$ and velocity V, is created in the material, where:

$$V = \lambda \bullet f = 2 \bullet L \bullet f = 2 \bullet L/T \qquad (2)$$

In the above equations, L is a representative material's dimension, such as the length of a thin section cylinder, and T is the resonance period.

The calculation of the elastic constants from measured resonance periods is achieved according to Spinner and Tefft [1].

Knowledge of the elastic properties of material is of prime

importance. These properties not only reflect the extent of bonding in the material, but also permit characterization of its behavior under stress, according to the following equations:

$$\sigma = E\varepsilon = E\frac{\Delta L}{L_0} \qquad (3)$$

$$\tau = G\gamma = G\frac{\Delta u}{L_0} \qquad (4)$$

$$\nu = -\left(\frac{\Delta r}{\Delta L}\right)\left(\frac{L_0}{r_0}\right) \qquad (5)$$

where ε and γ are the material's tensile and shear strain under the action of the applied tensile, σ, and shear, τ, stress, respectively.

Refractories and carbon electrodes are examples of heterogeneous materials containing pores, cracks and multi-phases aggregates. Such materials are generally exposed in service to mechanical abuse such as thermal shock, mechanical impact, abrasion and erosion. The foregoing promotes microstructural changes in the materials affecting their properties and consequently their behavior in service.

Non destructive acoustic testing is commonly used to characterize the microstructure of homogeneous materials such as fine ceramics and metals. However, it is usually difficult to apply such technique to refractories and carbon electrodes, and other such materials,

due to their heterogeneous nature. In the literature, the use of different acoustic techniques for the characterization of such heterogeneous materials has been reported [3-9]. Two categories of techniques are currently more involved for this purpose; the propagation techniques and the resonance techniques. In the first category of techniques, an acoustic pulse is forced to propagate into a sample under longitudinal mode. The reflected pulses at the sample's opposite boundaries along the propagation direction are collected and are used to calculate the acoustic pulse velocity which is then used to determine the longitudinal elastic modulus of the sample. Such techniques can be applied at room and high temperature. However, in the later instance, the use of waveguides between the samples and the acoustic pulse emitter and receiver make it difficult to detect the appropriate reflected pulses due to multiple reflections at each additional interfaces introduced by the waveguides.

In the second category of techniques, a sample is forced to vibrate either by the action of an imposed continuous acoustic wave or by the action of an impact. These techniques are currently referred as IET (Impulse excitation technique) and Resonant techniques, respectively. In both cases, the resonance frequency of the sample is collected and is used to calculate its elastic properties. The IET technique is currently more limited to the measurement of the flexural elastic properties of materials, both at room and high temperature.

In the resonant technique, the sample is currently more impacted by the action of a dropping ceramic or metallic ball, or by the action of a manual hammer. The sample's resonance period is then collected by the use of a standard piezoelectric transducer or microphone.

However, none of the reported apparatus and set-up thereof using the resonant technique allows the high temperature measurements of the overall set of elastic properties, e.g., the Elastic Modulus, the Shear Modulus and the Poisson's ratio. An example of a reported apparatus allowing such overall measurements at room temperature is the Grindo-Sonic apparatus commercialized by the company J.W. Lemmens, Inc., Bridgeton, Mo.

This apparatus consists of a module that converts the signal collected by a piezoelectric transducer to vibration periods, when a sample is manually impacted at room temperature under three distinct vibration modes; namely, longitudinal, flexural and torsional. According to the manufacturer, the period values issued from that module are the average of eight consecutive resonance periods collected from the tested sample. A DOS software is then used to calculate the elastic constants from these periods. This apparatus has more recently been used for high temperature testing of the flexural elastic modulus of refractories using one pneumatic hammer and one undefined microphone [2].

SUMMARY OF THE INVENTION

The present invention is directed to a method and apparatus for determining the elastic properties of materials comprising (i) one or more remote controlled impacting devices each able to strike one or more samples of said materials at any desired location in any desired direction (ii) one or more high frequency response microphones designed and positioned to capture audio impulse created by impacts of said hammers on said samples and deliver signals generated by said impulses to (iii) a

computerized electronic processing unit which provides and stores information provided by said impulses on the values of said properties.

One embodiment of said invention is directed to determination of said properties in homogenous materials such as fine ceramics and metals. A further embodiment of said invention is directed to determination of said properties in heterogeneous materials such as refractories and carbon electrodes. Yet a further embodiment of said invention is directed to determination of said properties at room temperature. In a preferred method and apparatus for practicing said further embodiment, a mounting table is used around said samples for appropriate positioning of said impacting devices and microphones.

Yet a further embodiment of the invention is directed to determination of said elastic properties at elevated temperature. Another embodiment of the method and apparatus for said elevated temperature determinations comprises a furnace for heating said samples, one or more impacting devices to strike said samples in the desired places and directions together with one or more waveguides inserted through the furnace lining to collect the audio signals from said samples created by said impacting devices and delivering said signals to one or more said microphones.

Said elastic properties determined by all said embodiments include Elastic Modulus, Shear Modulus and Poisson's ratio.

Figure 1 illustrate a signal processor (A) according to an illustrative embodiment of the present invention. That processor uses

novel high frequency response electrets microphones (B1 to B4) specially designed to capture fast audio impulses coming from hammer impacts (C1 to C4). The resonant frequencies collected by the microphones are analysed by the processor using a technique similar to FFT (Fast Fourier Transform). The signal is electronically processed with an ultra fast special Analog to Digital converter featuring very accurate timing. Mathematical calculations are made using a novel algorithm in order to achieve high speed output (< 100mSec) during the prominent resonance period, which corresponds to the average value of up to 2000 consecutive periods collected by the system during each impact. This confers to the MicroSonic apparatus higher repeatability of the results as compared to existing equipment.

The aforementioned algorithm is included in a new data acquisition Excel based software, called "SonicByte" as a trade name. The latter uses the period readings and presents the results on the computer screen (D) as well as storing repetitive results and maintain a data bank that can be consulted further. That software allows viewing of the raw signal and the period spectrum after each impact.

A computer port is used for communication with a 4-Channels Hammer Control Box (E). This provides computer controlled single and repetitive hammering of the sample. Using a controlled hammer instead of a manual hammer greatly increases chances of repetitive measurements, simply because a repetitive reading is, amongst other features, sensitive to the hit location.

Other objects, advantages and features of the present

invention will become more apparent upon reading the following non restrictive description of preferred embodiments thereof, given by way of example only with reference to the accompanying drawings.

DETAILED DESCRIPTION OF THE INVENTION

The MicroSonic system uses four electric hammers to repetitively hit the sample at the same spot every time, at four distinct locations (F). Such impacting repeatability can not be achieved when the sample is hit with a manual hammer.

For room temperature testing, the MicroSonic system uses a Mounting Table for Hammers and Microphones disposition around the sample at appropriate positions: Hammer C1 with Microphone B1 for flexural test in one direction, Hammer C2 with Microphone B2 for flexural test in a second orthogonal direction (with respect to the previous direction), Hammer C3 with Microphone B3 for longitudinal test and Hammer C4 with Microphone B4 for torsional test. The distance H between Hammer C4 and surface J of the sample, as well as the distance G between Microphone B4 and surface I of the sample is equal to 0.21 L_o, where L_o is the length of the sample. Hammer C4 and Microphone B4 should be located close to the edge of the samples J and K, respectively.

For high temperature testing, a specially designed furnace (P) and set-up is used, as shown on Fig. 2. In this case, ceramic waveguides (N1 to N4) are fixed to the microphones (L1 to L4, respectively) and inserted through the furnace lining to collect the audio

signals from the sample following impacts with the use of novel electric impacting devices (M1 to M4) coupled with ceramic hammers (O1 to O4, respectively) in the form of rod or tubes. The dimensions as well as the composition of these ceramic hammers are not critical. They should be chosen such that they are resistant to the impact energy as well as to the operating temperature and atmosphere inside the furnace. The relative position of the hammers and microphones for high temperature testing should be the same as those appropriate for room temperature testing (see Fig. 1). In both instances, the different signals recorded allow the SonicByte software to calculate and report the following elastic constants of the sample: Elastic Modulus (in two orthogonal directions), Shear Modulus and Poisson's ratio. The measurement of the flexural resonance period along two orthogonal directions allows for determination of the size of major defects in the aforementioned test samples.

With these two flexural resonance period measurements, the SonicByte software uses mathematical equations allowing the calculation of the equivalent equidistant and uniform crack lengths in the sample, such that the distance between these cracks is less or equal to their length.

The present invention with regard to (1) - The Data Acquisition and Resonance Period Calculation Algorithm, (2) - The Short Impact Microphones, (3) – The Electric Hammers and (4) – The Method of Calculation for determining Defects Size in tested materials, is described in the following sections.

The Data Acquisition and Resonance Period Calculation Algorithm

This section explains the principles which provide the basis of the algorithm permitting an adequate selection of period values corresponding to the resonant frequency present in an electric signal received by an appropriate apparatus such as the MicroSonic Data Acquisition Hardware System.

- **Data Acquisition and Resonance Period Calculation Algorithm criteria**

1- The algorithm execution should be as fast as possible.
2- The algorithm should have the ability to accept or reject information pertinent to the expected results.
3- The algorithm should have the ability to quickly react to sudden incoming information.
4- The algorithm should have the ability to use different parameters for treating information from different qualities of raw signals.

In the present application, the available information is essentially the rate at which an electric signal passes to zero volts. This information is transmitted from the electronic apparatus in the form of binary data. The binary words are representing the elapsed time between one zero volt event and the next one. Except for the first zero volt detection, all subsequent zero volt events are evaluated. The goal of the algorithm is to treat this information statistically and render an average value representing the most repetitive values for each zero volt event.

A well known mathematical approach already exists for treating vibration information called Fast Fourier Transform (FFT). These types of analysis require a substantial amount of computation and therefore perform slower than the algorithm proposed herein. Furthermore, FFT requires a near infinite signal in order to render information accurately. In the present instance, vibration information is only available for a very short period of time of the order of 1/5 of a second in most cases. FFT is not the most appropriate mathematical tool for the present application. The algorithm devised in the present invention is able to complete an analysis within a ½ second thereby satisfying criterion No. 1.

The information received by the electronic apparatus is comprised of elapsed time values that are often detrimental to the requested answer due to environmental noise and other not too well understood phenomena. The proposed algorithm has a near perfect ability to distinguish between unusable and usable readings. This satisfies thereby criterion No. 2.

Because the algorithm is constantly kept in a state of readiness in a computer, it is able to commence computation as soon as a signal arrives from the electronic apparatus. This satisfies thereby criterion No. 3.

Experimental information has indicated that the acoustic signal from an excited sample is sometime very weak and of extremely short duration. Such a situation forces the analysis to be made using

slightly different comparison criteria. The algorithm uses two parameters, namely the Ratio and the Bit depth, in order to cope with such situations. This satisfies thereby criterion No. 4..

- **Principal of the Algorithm of the Present Invention**

The algorithm of the present invention has been designed to provide acquisition of data and calculation of resonance period. The SonicByte main module is at the basis of a new and innovative data acquisition procedure for treating raw data. The main goal for this new algorithm is selectively to reject or retain reading points representing one or more resonant frequencies from an electric signal. Once mechanically impacted, a material sample will generate acoustic waves captured by a microphone and transformed into an electric signal detected electronically. This electronic circuit calculates the duration of each period and sends the values to the computer running the algorithm.

The algorithm is formulated in such a way to select most of the periods corresponding to the resonant frequency emanating from the sample under test. The main principle on which the algorithm is based involves the creation of many groups of period identified as being identical. Statistically, the group containing the most numerous periods is then identified as representing the periods corresponding to the resonant frequency of the sample.

A first analysis is performed using period values with a

resolution of 2 bits. Groups are then populated and identified by their population, then retained or rejected. Within the retained groups, another analysis is then repeated with 3 bits of resolution. The process is repeated up to 15 bits. The final result leads to the identification of two most numerous period groups. Those two groups represent the upper and lower limit of an accepted period value range.

An arithmetic mean is then calculated taking in account all period values within the range leading to the average period value of the main signal, hence the resonant frequency.

- **Practical Data Acquisition and Resonance Period Calculation Algorithm Detailed Description**

Data received from the MicroSonic Data Acquisition Hardware System correspond to an arithmetic value of the time required for an electric signal to pass from one zero volt value to the subsequent zero volt value. In resonating material, all values would in theory be identical. In reality, previous experimentation has shown that they are not identical. An adequate selection allows the user access to usable resonant frequency values.

Period values are transmitted to the computer with a resolution sufficient to enable the algorithm to supply adequate information. This resolution has arbitrarily established a value of 16 bits. However, other resolution values could be adequate and are included as

being within the scope of the present invention. In order to reject or accept acquired period values, the algorithm groups them. One group is composed of periods for which the values are identical for a resolution from 2 up to 15 bits. This is achieved according to the following steps:

First step: The algorithm identifies the number of periods contained in each group. The first analysis resolution is arbitrarily established to 2 bits. Other starting resolutions are also adequate and are included as being within the scope of the present invention.

Second step: The algorithm determines the population of the most numerous group. This value will be used as a comparison reference for accepting or rejecting all other groups.

Third step: Using an arithmetic parameter called Ratio, the algorithm calculates which group is accepted or rejected. The Ratio is arbitrarily established to have a value of 1/3. Other Ratios are also within the scope of the present invention and the user can utilizes the software to make the desired change. The acceptability level is calculated by multiplying the most populated group number of individual identical values by the Ratio. This value becomes the level at which the compared group is evaluated.

Step four: At this level, the selection or rejection of values by the algorithm takes place. The previously calculated level is then used by the algorithm to compare the group population obtained in step 1. This group

of values is retained if the population thereof is equal or higher than the level previously determined in step No. 3.

Step Five: When all groups have been either rejected or retained for further analysis, the said analysis is re-started by the algorithm using only retained values from all retained groups, with the exception that one more bit is added to increase resolution. Stepping one more bit is one acceptable option but other options are also acceptable such as, but not limited to, n+2 or n+3 or n*2, etc... and are included as falling within the scope of the present invention.

Step Six: This step establishes the maximum resolution at which the algorithm will cease analysis. A constant can be set by the user within the range of 5 to 15 bits. The proposed default is 15 bits. Previous experiments have shown that between 7 to 15 bits, results are satisfactory. The setting is usually efficient at 15 bits but in some severely deteriorated samples, a lower value is preferable. The algorithm will then progressively eliminate values from step 1 to step 5. When elimination process ceases, two groups are retained. The two groups are populated with period values representing the upper and lower limits.

Step Seven: A new group is created by the algorithm including all values from the upper and lower groups, and also all those rejected that fall within the upper and lower levels.

Step Height: The algorithm will then calculate the average value from all values retained in step 7. The sum of all values retained is divided by the number of values thus giving the average value.

Step Nine: The algorithm will display a table including three columns. Column 1 is the number of the value in order of event starting by number 1 then 2 and 3, up to the last value number. Column 2 includes the corresponding accepted value. If rejected, the field remains blank. Column 3 includes the corresponding rejected value. If accepted, the field remains blank. This table is used to create a point by point graphic. The X axis represents each point in time from first to last. The Y axis represents the value of each point. Points rejected or accepted are shown in different colors. Such graphic gives a useful and quick impression of the resonant phenomenon taking place in the sample.

In certain instances, the graphic will display bands of points leading to a perception of repetitive period values not identified by the algorithm. In such a situation, the algorithm parameters could be changed to target more appropriately the desired band of periods. The graphic then becomes a very useful tool for the user.

This Data Acquisition and Resonance Period Calculation Algorithm confers to the MicroSonic apparatus more repeatable determination of the elastic properties of heterogeneous materials, as compared to stat-of-the-art apparatus (see Example 1).

The Short Impact Microphones

- **Acoustic signal detection criteria**

1. The detection acoustic frequency range should be within the resonant frequency range of the targeted material samples to be analyzed.

The acoustic wave velocity in heterogeneous materials, such as refractories and carbon electrodes is most often lower than 3000 m/s. Samples made of such materials to be tested with MicroSonic apparatus typically have minimum dimensions of 0.5 x 0.5 x 3 inches. This leads to typical maximum resonant frequency to be detected of about 20 KHz.

2. The mechanical properties of the acoustic sensor should be such that it should be durable for industrial use.

For this purpose, the acoustic sensor is preferably encased in a heavy duty metal container and attached to a vibration-absorbent material. The sensor electric connection must be protected from manual handling by the help of a strength relief mechanism.

3. The acoustic detection should be directional to avoid environmental noise capture

To increase period measurement repeatability and accuracy, environment noise is avoided as much as possible in order to maintain a

clean acoustic signal from the vibrating sample.

4. The detection acoustic sensitivity should be as high as possible.

Due to previous impacting criteria No. 1, the acoustic sensor must be able to detect very low level energy impact.

5. The acoustic sensor should be insensitive to electromagnetic perturbations.

Another source of noise present in the electrical signal sensor output, apart from acoustic environmental noise, is electromagnetic perturbations. Thus, a metal shield protects the sensor.

6. The sensor should be made in such a way that the acoustic termination input is easily attachable to a waveguide for high temperature testing.

For high temperature testing, the use of a waveguide allows to avoid sensor destruction by excessive heat. Such waveguide can be easily attached to the sensor.

7. The electric output tension: acoustic pressure ratio of the sensor should be as high as possible.

Increasing the aforementioned ratio simplifies the sensor pre-amplification electronic stage of the acquisition system hardware, therefore minimizing its cost.

8. The sensor design should be as simple as possible to minimize the fabrication cost.

In an effort to minimize production cost, it is appropriate to limit the sensor characteristics only to those necessary to fulfill the above criteria No. 1 to 6.

- **Practical acoustic signal detection**

Different types of acoustic sensors are currently available on the market which could be classified into three categories: electromagnetic microphones, condenser microphones and electret microphones.

Electromagnetic microphones are based on the principle of a moving coil inserted inside a magnetic field. Such device is moved by variable acoustic pressure and translates this variation into an electric signal. Such device has a very low tension output, in the order of millivolts, which requires sophisticated high gain pre-amplification. With such device, criterion No. 7 is not respected. Moreover, these types of sensors are known to be more prone to destruction under severe mechanical shock, which violates the requirement of criterion No. 2. Therefore, for all these reasons, this type of device is not the best choice for microphone fabrication in the present application.

Condenser microphones are based on the principle of an electrically conductive membrane inserted into a high electric field. The acoustic pressure moves the membrane, therefore changing its tension

output compared to the electric field source. This voltage change is representative of the acoustic pressure variation. Such devices are generally used in high accuracy measurements where frequency response must be flat over a wide range, typically between 10 to 100 KHz. Such devices are difficult to manufacture, and therefore expensive (see criterion No. 8). This type of device is not the best choice for microphone fabrication in the present application.

It should be mentioned that both electromagnetic and condenser microphones are usually much bigger than electrets microphones. This is another reason why electret microphones are more appropriate for the present application.

The principle of the electret microphones is similar to the condenser microphones with two major exceptions: (1) – The electret microphones do not require a high voltage polarization field because they are pre-polarized and (2) – The electret microphones are manufactured with a built-in pre-amplifier which is in concordance with criteria Nos. 4 and 7. These types of microphones are the best suited for the present application. However, commercially available electret microphones do not respect the overall above acoustic signal criteria.

An electret microphone assembly for use with the aforesaid method and apparatus of the present invention for non destructive testing of the elastic properties of materials will now be described. A schematic of such acoustic detection device assembly is shown on Fig. 3.

An electret microphone (B) is fixed inside a metallic casing

(C) with the use of an intermediate material (D) the purpose of which are to fix the microphone and to absorb mechanical shock, as per the criterion No. 2. The electret microphone allows detection of 20 KHz maximum acoustic vibration, as per criterion No.1. The presence of the metallic casing enables criteria Nos. 2 and No. 5 to be met. The geometry and dimensions of this casing is not critical. However, the preferred geometry is close to a cylinder having a length, as well as an inner and outer diameters of close to about 3, 5/8 and 3/4 inches, respectively. At one end of the metallic casing in fixed a metallic tube (A), as a waveguide, the purpose of which is to meet the requirement of both criteria No. 3 and 6. The dimensions of the tube are critical since they set the directional response of the microphone. Typically, the length of the tube should be at least ten times its inner diameter. Said diameter is not smaller than the microphone receiving area, which is a hole typically 2 mm in diameter.

The electret microphone (B) is fixed with the shock absorbent material close to the end of the tube inside the casing but not touching it. For high temperature testing, the tube (A) is inserted inside the high temperature waveguide.

With such simple acoustic detection device, criterion No. 8 is met.

Such acoustic detection device assembly is shown hereinbelow with reference to Example 5.

The Electric Hammers

- **Impacting system criteria:**

1. The sample is immobilized on it support during impact to prevent friction noise.

Laboratory experiments have shown that stronger impacts promote sample displacement on the support, therefore creating friction noise, which is detrimental to the purity of the acoustic resonant impulse emanating from the sample. Consequently, analyzed values are more prone to uncertainty. This condition is prevented by minimizing mass momentum of the hammering system prior to impact. This could be achieved in either or both of two ways: minimizing either the mass and/or the velocity of the moving parts.

2. The impact should not impair the properties of the sample.

To prevent sample impairment during impact, the impact stress should not exceed the sample's strength. This could be achieved by increasing the impact surface and/or reducing the impact force. Said force may be controlled by adjusting the mass and/or the velocity of the moving parts and by providing an impact surface that is higher than the maximum defect size in the sample.

3. The impact should appropriately excite the sample to produce a detectable acoustic impulse.

Heterogeneous materials such as refractories are acoustically absorbent. Thus, sufficient impact energy must be applied to the sample to generate stationary waves in the various tests of vibration modes. This energy may be controlled by adjusting the mass and/or the velocity of the moving parts.

4. Ideal impact conditions for testing under torsion or flexion requires minimizing the impact surface.

Pure stationary waves under torsion or flexion are known to be most efficiently created when impact surface is nearly zero. This thus favors the use of small diameter impacting tip.

5. The impact should be single to prevent resonant acoustic signal contamination produced at the beginning of movement transmission.

Experimental observation has shown that the first part of the signal collected after impacting a heterogeneous material is composed of acoustic noise. Therefore, any uncontrolled successive impacts following the first excitation are undesirable. To prevent repeated impacts, the impact tip should not be allowed to rebound on the sample.

6. For repetitive tests, the impact position should be maintained.

According to the previous section, specific impact locations allow to produce vibration in specific modes (see Fig. 1). The impacting system should thus allow movement of the impact tip strictly along the

axial direction.

7. For high temperature testing, the impacting mechanism must be at a sufficient distance from the furnace hot zone.

Most impacting system parts embody materials have low resistance to elevated temperature and thus must be protected from excessive heat.

- **Practical impacting system optimization:**

For high temperature testing, ceramic rods or tubes are used as impact tips. Such materials should be resistant to the furnace operating temperature and atmosphere, as well as to high temperature mechanical impact and thermal shock. Any such materials from the group of technical or advanced ceramics, such as alumina, mullite, silicon nitride, silicon carbide, boron carbide and others may be useful for this purpose. A ceramic impact tip made of a tube should preferably have a closed end hitting the sample. Moreover, the closed end should preferably have a radius of curvature equal to the tube diameter. The reason for such curvature requirement is to tolerate imperfect hitting angle which should be as close as 90 ° as possible. Such preferred geometry limitation also applies to ceramic impact tip made of a rod.

With respect to the above geometry limitation and impacting criterion No. 2, the tip diameter should exceed the major defect size in the test material. As an example, refracories frequently contain microstructural defects not exceeding 6 mm. In such a case, the minimal ceramic tip

diameter should be 6 mm.

According to criterion No. 7, the tip length should be long enough to permit convection and/or radiation cooling in such a way to protect the impacting parts. The non-ceramic parts of the impacting system should not exceed a temperature higher than the maximum service temperature of the most sensitive part inside the impacting mechanism. This criterion limits the minimum length of the ceramic impact tip.

The above dimension limitations dictate the mass of the specific ceramic tip used. With respect to most above criteria, this mass should be minimal. Therefore, the use of tubes with ceramic tips instead of rod is preferred.

Pneumatic, hydraulic and electromagnetic impacting systems involved several metallic components. While the present invention is not limited to a specific type of impacting system, the use of an electromagnetic impacting system is preferred. Such a system includes a ferromagnetic core, such as iron-based alloys in the form of a rod, which is contained inside a solenoid. An electric current passing through the said solenoid induces a magnetic field that promotes the displacement of the core along the solenoid axis.

The foregoing impact device comprising an electromagnetic component coupled to the above-described impacting tip is considered to be within the scope of the present invention.

A schematic of such impacting system is shown on Fig. 4. This system involves two solenoid activators coupled in series (A and B) which share one iron-based alloy, in the form of a rod, as the ferromagnetic core (C). Solenoid (A) and (B) promote back and forth displacement of the core along the solenoids axis, respectively. The ferromagnetic core (C) is fixed to the ceramic tip (K) by the use of an intermediate thin metallic rod (D). The nature of this rod as well as its diameter is not critical. Both should however be such to minimize the mass of the impacting system moving parts. The interfaces (E), (F) and (G) are preferably fixed with the use of glue.

According to criterion No. 5, a spring (H) is located at one end of the intermediate rod (D) to prevent uncontrolled successive impacts following the first sample excitation. Moreover, the ferromagnetic core (C), after movement initiation, is mechanically stopped with the use of two stoppers (I) and (J). When the core reaches the stopper (I), its velocity is maximum. At this point, the core is suddenly decelerated to a zero velocity. Therefore, the rest of the moving parts, including the spring (H), the intermediate rod (D) and the ceramic impact tip (K) start to loose mass momentum. The loss rate is determined by the spring rigidity, the moving parts velocity and their mass. The distance between the impact tip (K) and the sample (L) at the moment when the ferromagnetic core is stopped should be minimal. This distance should preferably be less than half of the displacement of the impact tip (K) from its position when the ferromagnetic core (C) is stopped, and its position when it reaches zero velocity after being decelerated by the spring (H) in the absence of a sample. In such conditions, when the tip reaches the sample (L), the moving parts transfer mechanical energy to the sample and then rebounds. The spring (H) will

then pull back the moving part and retain them away from the sample. In such conditions, the synchronization of the solenoids control signals with the moment of impact is not critical, therefore easier to control. It should be noted that the purpose of the second stopper (J) is to fix the position of the core when the moving parts are pull back with the solenoid (A).

With respect to criterion No. 6, the intermediate rod (D) is supported by two low friction supports (M) and (N). The distance between the two supports should be as great as possible without interfering with the movement of the moving parts. The position of support (M) should be as close as possible from interface (E) when moving parts are retracted away from the sample. Moreover, the position of support (N) should be as close as possible to the interface (F) when moving parts are in the most forward position toward the impact direction when the sample is absent. This positioning assures free movement and least friction on both supports due to reduced bending moment when the impact is in the horizontal direction.

The length of the intermediate rod (D) should be such that it minimizes the rod deflection, the static friction coefficient at the supports-rod interfaces as well as the looseness of the impacting moving parts. In such conditions, repetitive sample impacting at locations not differing by more than half the ceramic impact tip diameter, with respect to the targeted location, should be achievable.

According to criteria Nos. 2 and 3, the impacting velocity of the moving parts must be closely controlled to allow sufficient energy transmission to the sample with no deterioration.

Apart from the mass of the impacting moving parts, their velocity is influenced by both static and dynamic friction coefficients of the two supports (M) and (N), as well as by the solenoid excitation signal duration and strength. Static and dynamic friction coefficients of the supports must be as low as possible to maximize free movement. For these reasons, the supports are preferably made of Teflon.

For a given set of solenoids characteristics, the electrical excitation duration, strength and synchronization must be such that (1) - the impact tip reaches the sample at proper velocity, (2) - they allow enough time for oscillation attenuation of the impacting moving parts system and (3) - they allow retraction of the moving parts to get ready for the next hit.

The impacting device, as described in the foregoing passage, is shown in Example 6.

The Method of Calculation for determining Defects Size

The surprising discovery has been made that defects such as pores and cracks in virgin heterogeneous materials, such as refractories, may be unequally distributed on their boundaries such that the measurement of their flexural resonance period along two orthogonal directions lead to the determination of the defects size on their more damaged boundary. More surprising is the fact that the equation from which such determination is achieved can be deduced from the theory concerning the natural flexion resonance frequency of a perfectly elastic rectangular beam. In fact, the afore-mentioned condition is non-realistic

with heterogeneous materials such as refractories, which most often present non-elastic behavior.

The natural flexion resonance frequency of a rectangular beam is given by the following two equations:

$$f = \frac{1}{T} = \frac{\pi}{2}\sqrt{\frac{EI}{ml^4}} \qquad (6)$$

$$I = \frac{bh^3}{12} \qquad (7)$$

Where:

f = Natural flexion resonance frequency [Hz]
T = Natural flexion resonance period (sec)
E = Bulk elastic modulus [Pa]
I = Linear moment of a rectangular beam [m^4]
l = Specimen length [m]
b = Specimen width [m]
h = Specimen height [m]
m = Linear density [kg/m]

Thus:

$$f \propto \sqrt{I} \qquad (8)$$

By referring to Fig. 5, let us consider the following equations:

$$I_{//} = \frac{b_{//} h_{//}^{\;3}}{12} \qquad (9)$$

$$I_{\perp} = \frac{b_{\perp/} h_{\perp}^{3}}{12} \quad (10)$$

Where

$I_{//}$ = Linear moment of the non-damaged region of a rectangular beam parallel to the crack direction [m^4]

$I_{\perp}$ = Linear moment of the non-damaged region of a rectangular beam perpendicular to the crack direction [m^4]

From equations (8), (9) and (10), the following equations can be written:

$$\frac{f_{//}}{f_{\perp}} = \frac{h_{//}}{h_{\perp}} \quad (11)$$

Since the flexion resonance frequency (f) is the inverse of the flexion resonance period (T), equation (11) becomes:

$$\frac{T_{\perp}}{T_{//}} = \frac{h_{//}}{h_{\perp}} \quad (12)$$

According to fig. 5, the following equations can be written:

$$h_{\perp} = h_O \tag{13}$$

$$h_{//} = h_O - a \tag{14}$$

Thus:

$$a = h_O\left(1 - \frac{T_{\perp}}{T_{//}}\right) \tag{15}$$

According to equation (15), the measurement of the natural flexion resonance period of a perfectly elastic rectangular beam along two orthogonal directions could theoretically lead to the size of the defects in the material being located on its more damaged orthogonal surface with respect to these two directions. This should however be the case only when the distance between these defects is such that it prevents the transfer of vibration between the damaged and non-damaged regions of the beam. This condition is theoretically met when the distance between the cracks is less than their length (see Example 2), since in such condition cracks interaction is possible. It has surprisingly been observed that this condition may be met within virgin heterogeneous materials such as refractories (see Example 3). More generally, the value of "a" in equation (15) could be interpreted as the equivalent equidistant and uniform cracks length in the material, such that the distance between these cracks is less than or equal to their length. It then becomes possible with such a tool to classify materials with respect to the extent of their damage (number and size of cracks) (see Example 4).

Example 1:

This example shows that The Data Acquisition and Resonance Period Calculation Algorithm used with the MicroSonic apparatus confers on said apparatus more repeatable determinations of the elastic properties of heterogeneous materials as compared to state-of-the-art apparatus.

In this example, both the MicroSonic and the Grindo-Sonic (model MK-4) apparatus were used to measure the room temperature elastic properties of three pre-fired 230 x 115 x 65 mm refractory castable samples. Samples A1 and B1 were prepared from the same silicon carbide-based castable, either pre-fired at 1200 °C (samples A1) or 815 °C (samples B1). Samples C1 was prepared from a zircon-based refractory castable pre-fired at 1200 °C.

The results obtained are presented in Tables I to III. These results are the average period (T) and their standard deviation (s) values calculated from a series of 30 successive measurements, with both apparatus, in each tested conditions, i.e., longitudinal (L), flexural in two orthogonal directions (F$_{//}$ and F and torsional (T).

As can be seen from these Tables, the MicroSonic apparatus is, in general, capable of greater repeatability of its results due to its lower corresponding standard deviation values. This is particularly true for sample B1 which, under longitudinal mode, led to results having a standard deviation of about 50 times less with the use of MicroSonic (see Table II). As shown in figure 6, the Grindo-Sonic failed in detecting the

more predominant resonance mode when multi-modes propagate simultaneously in the sample (as shown by the large spectrum computed by the SonicByte acquisition software during testing sample B1 under longitudinal mode with the MicroSonic apparatus).

Example 2:

This example is provided in order to show that the length of equidistant and uniform cracks located on one surface of a rectangular beam made of a refractory material may be determine with the use of equation (15) from the measurement of the natural flexion resonance period of the beam along two orthogonal directions.

In this example, a 160 x 30 x 25 mm aluminosilicate refractory castable sample, pre-fired at 1200 °C, was tested with the MicroSonic apparatus. The maximum aggregates and defects (pores and/or cracks) size in the sample were about 6.00 ± 0.05 mm and 8.00 ± 0.05 mm, respectively. Prior to the test, a 1 mm thick diamond saw was used to create 15 equidistant and uniform pre-cracks on one lateral face of the sample. The distance between the cracks as well as their length was about 10.00 ± 0.05 mm. This sample was tested under flexural mode along two orthogonal directions with respect to the pre-cracks orientation.

The use of equation (15) for said pre-cracked sample led to a calculated defects size of 9.91 ± 0.03 mm, which is very close to the pre-cracks length.

Example 3:

This example is provided in order to show that virgin refractories may contain non-uniformly distributed cracks on their boundaries, such that the distance between these cracks is less than their length, and consequently that the length of said cracks, according to this invention, may be determined from equation (15), following the measurement of the natural flexion resonance period of the material along two orthogonal directions.

The results presented in Example 1 for sample C1 tested with the MicroSonic apparatus under flexion in two orthogonal directions were put inside equation (15). The calculated defect size value so obtained was 7.69 ± 0.02 mm. Surprisingly, the maximum defects (pores and/or cracks) size measured from that sample was about 8.00 ± 0.05 mm.

Example 4:

This example is provided in order to show that equation (15) may be used to determine the equivalent equidistant and uniform crack lengths in refractories (see the definition given above), allowing the classification of such materials with respect to the extent of their damage (number and size of cracks).

The results presented in Example 1 for sample A1 and B1 tested with the MicroSonic apparatus under flexion in two orthogonal directions were introduced into equation (15).

The calculated defect size values so obtained were 1.42 ± 0.08 mm for sample A1 and 0.72 ± 0.14 mm for sample B1, despite the measured defects (pores and/or cracks) size for these two samples being about 6.00 ± 0.05 mm and 12.00 ± 0.05 mm, respectively. Considering the value of "a" in equation (15) as the equivalent equidistant and uniform crack lengths in the material (see previous definition), these results were suggesting that the amount of defects in sample A1 was higher than that in sample B1. This hypothesis was validated from open porosity measurements from both samples. A higher porosity for sample A1 was effectively obtained (22 vol. % as compared to 18 vol. %).

<u>Example 5:</u>

An example of an acoustic detection assembly according to Fig. 3 is given in the following.

In this example, with reference to Fig. 7, the casing of the assembly is made from five different parts supplied by Neutrix Company, USA., i.e., parts (A), (B), (C), (D) and (F). Tip (A) is part No. NM2P, Male-Male junction (B) is part No. NAM1, Male-Female Casing (C) is part No. NAM4 and Strain relieve assembly (D) and (F) is part No. CM.

The electret microphone (H) is available in bulk quantities from Addison T.V. Parts, Montreal, Canada. It is a 20 KHz maximum frequency response microphone and is in the form of a cylinder 5 mm diameter and 4 mm long. The mechanical shock absorber (I) is made of electronic grade silicon. In this assembly, a 1 nF none polarized 50 volts

capacitor (G) is connected in parallel with the electret microphone to further filter the electric signal. The connection wire (E) is made of a shielded wire and is used to connect the sensor to the electronic device.

Example 6:

An example of an impacting device assembly according to Fig. 4 is given in the following.

In this example, with reference to Fig. 8, a casing (D) contains the following components:

B: Front support made of a teflon cylinder, 1/2 in. length and 1/2 in. diameter, with a hole in the center, 1/8 in. diameter.

C: Support cylinder, 6 in. long with inner and outer diameter of 1/2 and 5/8 in., respectively. The cylinder is attached to the casing (D).

E: Back support made of a teflon cylinder, 1/2 in. length and 1/2 in. diameter, with a hole in the center, 1/8 in. diameter.

F: Front stopper made of silicon material, 1 in. diameter, with a hole in the center, 7/32 in. diameter. The thickness is 1/4 in.

G: Front copper wire solenoids having a maximum pulling force of 120 g on the moving core (J).The length is 1 3/4 in. The outer diameter is 1 in.

H: Rear copper wire solenoids having a maximum pulling force of 120 g on the moving core (J). The length is 1 3/4 in. The outer diameter is 1 in.

I: Rear stopper made of silicon material, 1 in. diameter, without central hole. The thickness is 1/4 in.

J: Ferromagnetic cylindrical core made of iron and having an outer diameter and a length of 0.31 and 2 1/4 in., respectively.

K: Spring made of conventional metallic material and having an elastic constant of about 10 g/mm. The spring inner and outer diameters are 1/8 and 3/16 in., respectively. The length is 1 1/2 in.

L: The intermediate metallic rod is made of 316SS and has a diameter of 1/8 in. The length is 12 in.

The ceramic impact tip (A) is made of high purity (> 98 wt. %) mullite fine ceramic tube having an inner and outer diameter of 5/32 and 9/32 in., respectively. The length is 12 in. The curved end of the tube has a curvature radius of 9/64 in.

Although the present invention has been described hereinabove by way of preferred embodiments thereof, it can be modified without departing from the spirit and nature of the subject invention, as defined in the appended claims.

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WHAT IS CLAIMED IS:

1. A method for determining the elastic properties of materials, said method comprising use of (1) one or more remote-controlled impacting devices each able to strike one or more samples of said materials at any desired location in any desired direction (2) one or more high frequency response microphones designed and positioned to capture audio impulses created by impact of said devices on said sample and deliver signals generated by said impulses to (3) a computerized electronic processing unit which provides and stores information provided by said impulses on the values of said properties.

2. A method according to claim 1 wherein said materials are homogeneous and include both fine ceramics and metals.

3. A method according to claim 1 wherein said materials are heterogeneous and include refractories and carbon electrodes.

4. A method according to claim 1 wherein said determination are made at room temperature.

5. A method according to claim 4 wherein a mounting table is used around said sample to enable appropriate positioning of said impacting devices and said microphones.

6. A method according to claim 1 wherein said determinations are made at elevated temperature.

7. A method according to claim 6 wherein said determinations are made using a furnace for heating one or more test samples, one or more impacting devices able to strike each of said samples in the desired locations and directions, together with one or more waveguides inserted through the furnace lining to collect the audio signals from said samples and deliver said signals to said microphones.

8. A method according to any one of claims 1 to 7 wherein said elastic properties include Elastic Modulus, Shear Modulus and Poisson's ratio.

9. A method according to claim 1 wherein said computerized electronic processing unit programmed to use an algorithm wherein (a) information is transmitted to said unit in the form of binary data representing the elapsed time between voltage impulses (b) said algorithm has the ability to accept or reject usable or unusable readings (c) is kept constantly in a ready status to start instant computation on receipt of a signal and (d) has the ability to use different parameters for treating information from raw signals of differing quality.

10. A method according to claim 9 wherein said algorithm creates groups of periods corresponding to the resonant frequency of said sample, said periods being identified as representing each resonant frequency.

11. A method according to claim 10 wherein said groups are further analyzed to identify groups representing the upper and lower

limits of said period values.

12. A method according to claim 11 wherein said analysis is made in a series of steps, said steps being:

(i) said algorithm identifies the number of said periods contained within each of said groups,

(ii) said algorithm determines the population of the most numerous group,

(iii) said algorithm calculates using an arbitrarily established ratio to determine which groups are accepted or rejected, said calculation determining the acceptability level by multiplying the individually identified values by said ratio,

(iv) said values are accepted or rejected to retain those values having a population equal to or higher than said value identified in step (iii),

(v) further analysis is continued using the values from all retained groups,

(vi) the maximum resolution at which the algorithm will cease analysis is established to eliminate progressively values from steps (i) through (v),

(vii) said algorithm creates a new group including all values within the upper and lower levels determined in the foregoing steps,

(viii) said algorithm calculates the average value from all values retained in step (vii), and

(ix) said algorithm provides data for a graphic display of test results.

13. A method according to claim 1 wherein said

determination uses the formula

$$A = abs[H (1 - (T sub 1 / T sub 2))]$$

where:

A represents the equivalent equidistant and uniform length of cracks in the material, such that the distance between said cracks is equal to or lower than said length;

H represents the specimen height along the impacting axis;

T sub 1 is the natural flexion resonance period along either (a) the height of said sample or (b) the width of said sample;

T sub 2 is the natural flexion resonance period along either (a) the width of said sample when T sub 1 measures the height or (b) the height of said sample when T sub 1 measures the width thereof.

14. An apparatus for determining the elastic properties of materials, said apparatus comprising use of (1) one or more remote-controlled impacting devices each able to strike one or more samples of said materials at any desired location in any desired direction (2) one or more high frequency response microphones designed and positioned to capture audio impulses created by impact of said devices on said sample and deliver signals generated by said impulses to (3) a computerized electronic processing unit which provides and stores information provided by said impulses on the values of said properties.

15. An apparatus according to claim 14 wherein said determination is carried out at room temperature with the use of a mounting table around said sample to enable appropriate positioning of said impacting devices and said microphones.

16. An apparatus according to claim 14, wherein said determinations are made at elevated temperatures using a furnace for heating one or more said samples, one or more impacting devices to strike said samples in the desired locations an directions and using one or more waveguides inserted through the furnace lining to collect the audio signals from said samples and deliver said signals to said microphones.

17. An apparatus according to claim 14, wherein said microphones are of the electret type each of which is (a) encased in a heavy-duty metal container and (b) able to detect maximum acoustic vibrations of 20kHsub3.

18. An apparatus according to claim 17 wherein said metal container is attached to a metallic tube which functions as a waveguide.

19. An apparatus according to claim 18 wherein said metallic tube is positioned inside a high temperature waveguide.

20. An apparatus according to claim 19, wherein (a) the moving mass of said impacting device can be varied at will (b) the impacting velocity of the striker can be controlled and varied at will and (c) the striker tip is prevented from rebounding on said sample, after each initial strike thereon.

21. An apparatus according to claim 17, wherein said microphones comply with detection criteria, said criteria being:

(i) the acoustic frequency detection range is within the resident frequency range of said sample,

(ii) acoustic detection is directional such that capture of environmental noise is avoided,

(iii) the acoustic sensitivity is high enough (i.e. higher than 45 dbA (decibel acoustic)) to detect low energy impact,

(iv) a metal shield is provided to prevent electro-magnetic perturbations, and

(v) the ratio electric output tension : acoustic pressure should have a minimum value of 10 millivolt/Pascal.

22. An apparatus according to claim A 7 wherein said impacting device complies with given criteria, said criteria being:

(i) said sample is prevented from moving during impact by (a) minimizing said moving mass and/or (b) minimizing said velocity,

(ii) the impact surface of said sample and/or the impacting force are controlled such that the impact stress does not exceed the strength of the sample,

(iii) the impacting energy is controlled by adjustment of the mass and/or velocity of said moving mass such that the impact excites the sample to produce a detectable acoustic impulse,

(iv) to test under torsion or flexion, the impacted surface is minimized by use of an appropriately dimensioned small diameter impacting tip whose surface is at least 400 times smaller than the impacted surface area,

(v) for repetitive testing , the impacting system allows movement of the impact tip strictly along the axial direction,

(vi) said impacting mechanism is protected during high temperature testing by locating said mechanism at least 10 inches from the hot zone of the furnace.

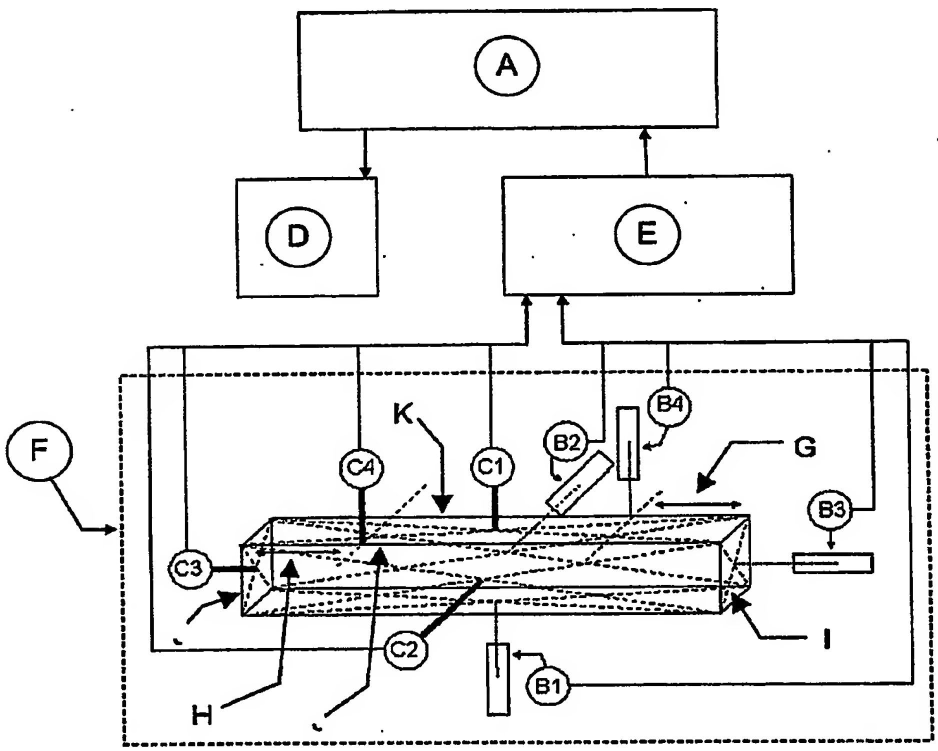

Fig. 1: MicroSonic Apparatus and Set-Up

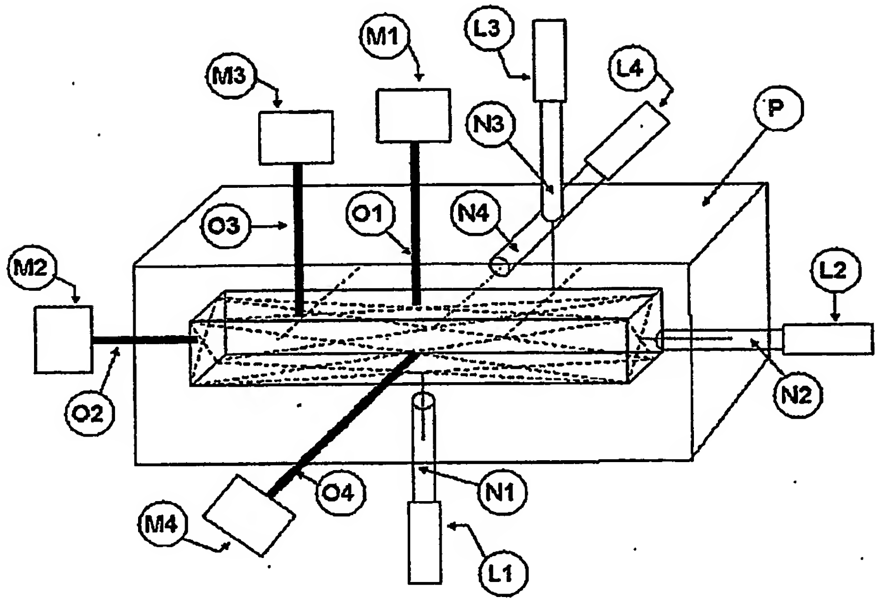

Fig. 2: Set-Up for High Temperature Measurement

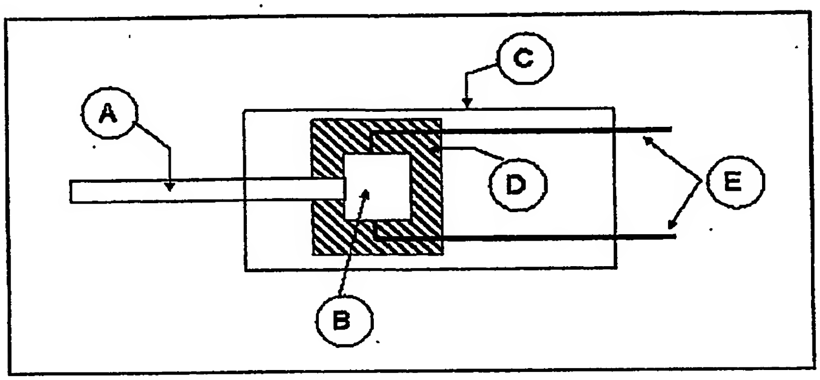

Fig. 3: Schematic representation of the acoustic detection device assembly.

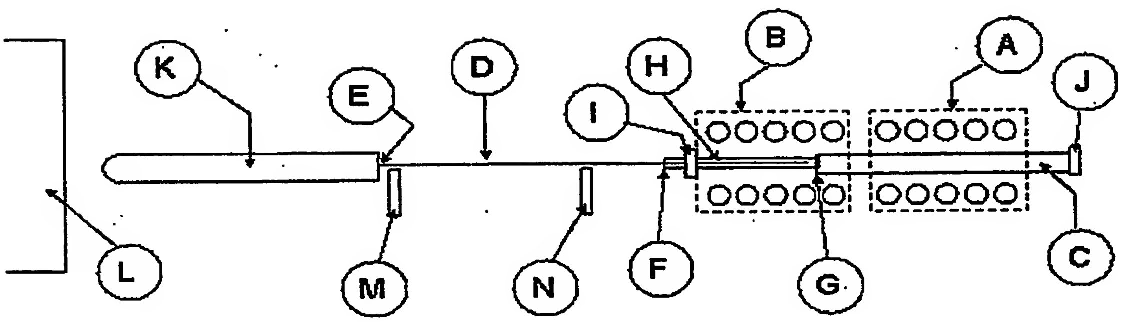

Fig. 4: Schematic representation of the impacting device assembly

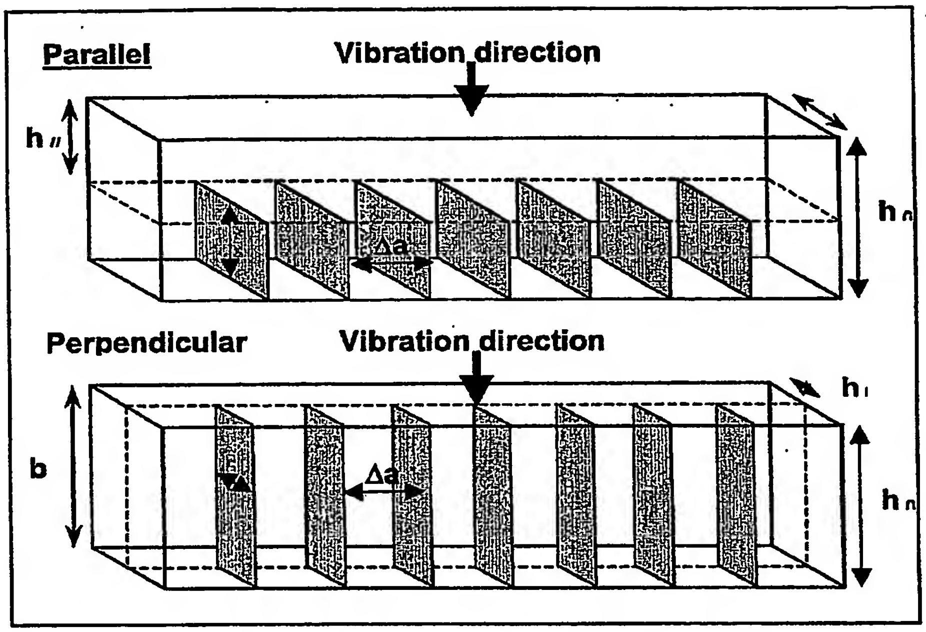

Fig. 5: Rectangular beam containing equidistant and uniform cracks on one lateral face and subjected to flexural vibration along two orthogonal directions.

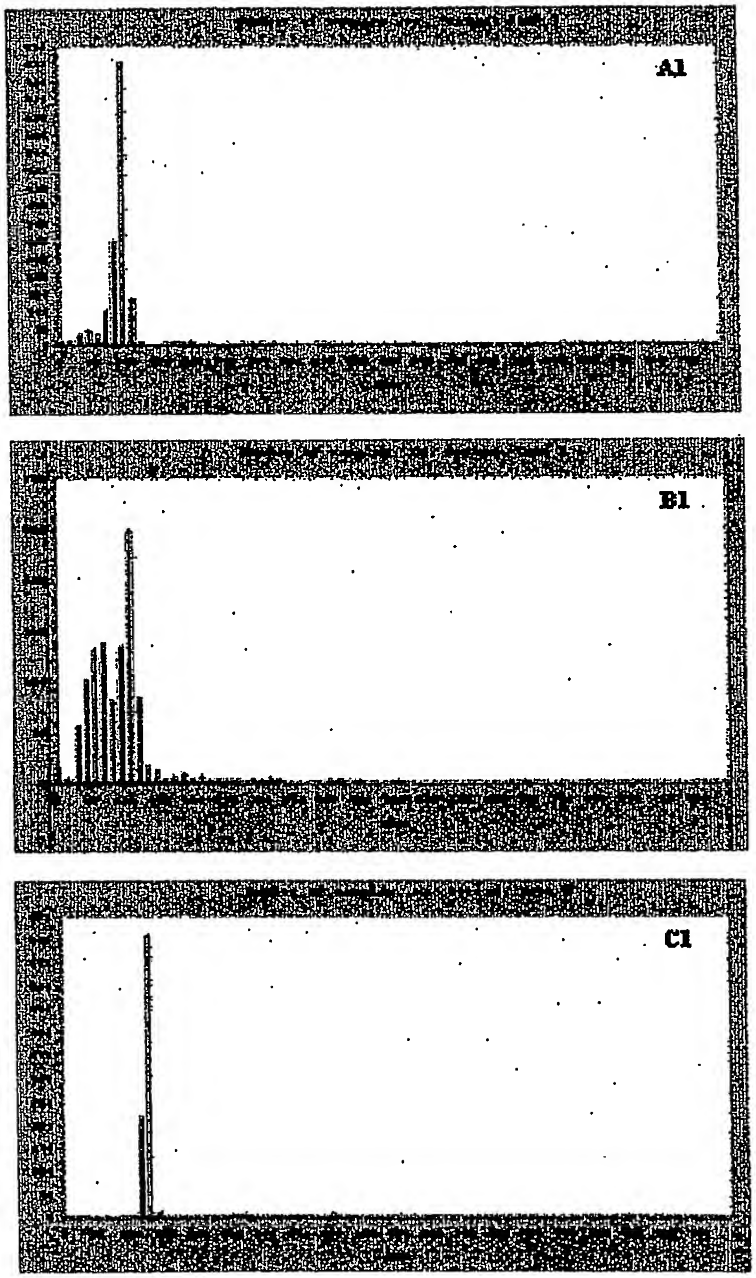

Fig. 6

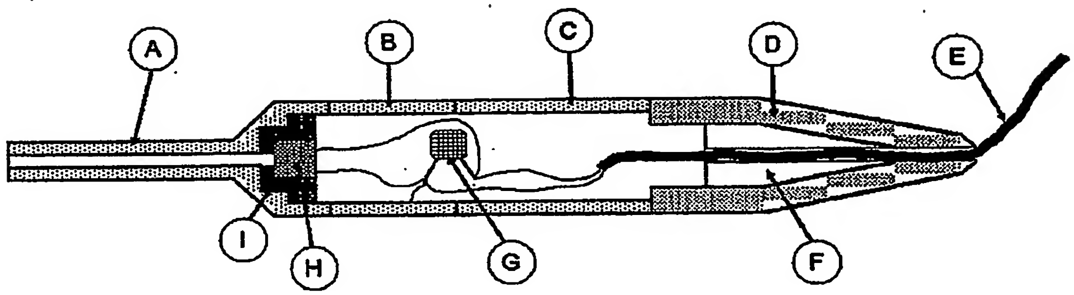

Fig. 7: Schematic representation of the preferred acoustic detection device assembly for 20 KHz maximum frequency response.

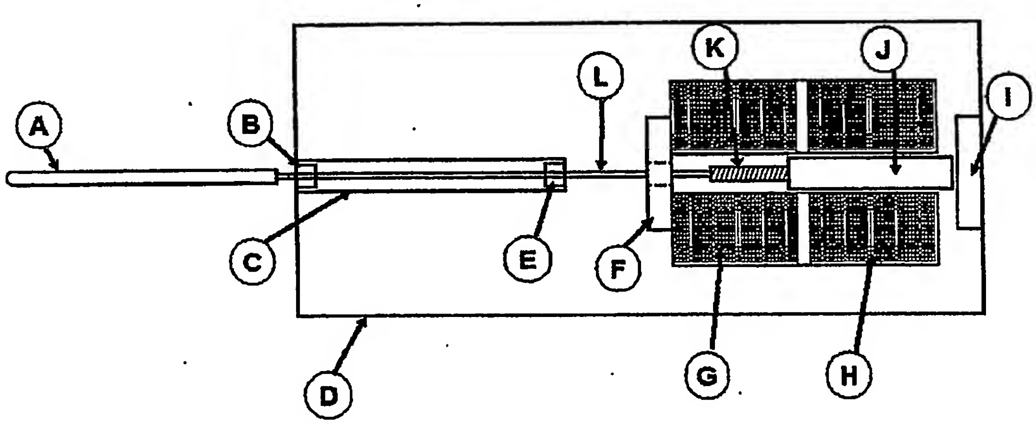

Fig. 8: Schematic representation of the preferred impacting device assembly for high temperature testing.

Table I: Sample A1

	GrindoSonic		Microsonic	
	T	S	T	S
L	100.6	0.7	101.1	0.5
F//	149.9	0.3	148.3	0.4
F⊥	216.1	1.6	212.4	0.5
T	199.1	0.9	200.9	0.3

Table II: Sample B1

	GrindoSonic		Microsonic	
	T	S	T	S
L	114.8	9.8	109.5	0.2
F//	161.4	0.3	158.2	0.7
F⊥	236.0	0.3	236.1	0.2
T	217.3	0.6	216.2	0.5

Table III: Sample C1

	GrindoSonic		Microsonic	
	T	S	T	S
L	137.7	0.2	140.5	0.1
F//	213.2	1.7	210.8	0.5
F⊥	300.2	1.6	293.8	0.7
T	263.0	1.2	266.0	1.2